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Enhancing GPS satellite code bias performance for PNT services

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ABSTRACT: Global Positioning System (GPS) flex power adjustment significantly impacts on the quality of Positioning, Navigation, and Timing (PNT) services. This is because conventional code biases provided by agencies often fail to fully meet the diverse and evolving user requirements. In response to this challenge, we propose an innovative code bias solution specifically tailored for GPS flex power scenarios. We begin by thoroughly assessing the performance of existing GPS code bias products, using them as benchmarks for comparison. Building on it, we introduce a novel code bias concept and elaborate on the estimation methodology. To precisely characterize code bias behavior, we develop a specialized metric that can effectively capture key performance dimensions. Experimental validation shows that the proposed solution remains compatible with conventional products during standard operations. Moreover, it demonstrates the ability to perform adaptive state transitions in response to complex conditions induced by flex power management. Comparative analysis across normal and flex power operational phases reveals multifaceted advantages for GPS, especially highlighting enhanced environmental adaptability and performance for PNT services, which are crucial for a wide range of applications.

KEYWORDS: Positioning, navigation and timing (PNT); GPS; Code bias; Flex power.

Introduction

Global Navigation Satellite System (GNSS), which operates as a space-based Radio Navigation Satellite System (RNSS), incorporates satellite constellations such as BeiDou Navigation Satellite System (BDS), Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), and Galileo. It has developed into a vital element of the global information infrastructure and the operational fabric of society. The systems provide uninterrupted, highly reliable, and precise Positioning, Navigation, and Timing (PNT) services, which underpin modern technological advancements and daily activities worldwide [Yang et al. 2021].

Nevertheless, space-based RNSSs are inherently vulnerable to certain technical vulnerabilities. For instance, they are prone to signal blockage, interference, and spoofing. The increasing likelihood of service denial and degradation in space-based PNT systems poses significant operational risks to national and societal critical infrastructures [Bian et al. 2021].

In light of these systemic vulnerabilities, the United States took the lead in introducing the concept of "navigation warfare". This concept aims to address the limitations of RNSS by pursuing specific strategic objectives [Li et al. 2018; Yang et al. 2017]. Since its inception, this conceptual framework has spurred rapid technological advancements, including the development of various technologies such as flex power, navigation denial capabilities, autonomous navigation systems, in-orbit satellite reprogramming, technical reconfiguration, and enhanced cybersecurity measures [Tang et al. 2020].

Navigation signal power adjustment technology, widely known as flex power, serves as a fundamental element in enhancing RNSS signals. It is of vital importance in upholding the robustness and availability of PNT services [Steigenberger et al. 2019]. The GPS system is equipped with sophisticated radio frequency reconfiguration functions. It relies on 31 operational satellites from the second and third generations, enabling agile and flexible signal management [Esenbuğa and Hauschild 2020]. The GPS flex power functions via frequency-domain implementation. It boosts the performance of the P-code signal while preserving the integrity of the C/A-code. This is accomplished by transforming the Coherent Adaptive Subcarrier Modulation (CASM) triple-signal multiplexing (involving C/A + P + M codes) into Quadrature Phase Shift Keying (QPSK) dual-signal modulation (comprising C/A + P codes).

In terms of historical implementation, initial testing occurred from September 7 to 12, 2010, with in-orbit experiments conducted on Block IIF satellites and Block IIR-M satellites. The Block IIR-M satellites were evaluated by measuring variations in the L1 band component using high-gain antennas [Jimenez-Banos et al. 2010]. In practical operational scenarios, GPS flex power was first deployed in military confrontations, such as the 2018 military actions in Syria and the 2019 operation in Iran. In these cases, after localized interference occurred, system-wide adjustments to the power of the P(Y)-code were implemented on Block IIR-M and IIF satellites to maintain the integrity of GPS services in conflict-affected areas [Han et al. 2019; Liu et al. 2018; Steigenberger et al. 2019]. Starting from February 14, 2020, GPS has shifted to conducting normalized flex power operations within specific fixed areas. However, ground control systems and receivers have yet to fully support the M-code. As of now, the P(Y)-code remains the primary authorized signal for power enhancement purposes [Li et al. 2022].

To address this challenge, Yang et al. [2022] proposed a machine-learning-based real-time monitoring system for GPS flex power. This system has achieved false alarm and missed alarm rates lower than 10^{-5} and 10^{-3}, respectively. Tang et al. [2022] enhanced traditional signal power detection techniques by employing Z-tracking algorithms to analyze variations in C/N_0 observations during flex power events. Flex power operations can induce code bias fluctuations ranging from sub-nanosecond to hundreds of nanoseconds [Esenbuğa and Hauschild 2020; Esenbuğa et al. 2023; Steigenberger et al. 2019; Su and Jiao 2023a; Wu et al. 2024]. Conventional code bias products with low temporal resolution fail to accurately capture the rapid variations caused by flex power operations. The hourly-updated broadcast ephemeris biases and daily or monthly post-processed products provided by institutions such as the Chinese Academy of Sciences (CAS), the German Aerospace Center (DLR), and the Center for Orbit Determination in Europe (CODE) inevitably degrade satellite availability and the quality of PNT services [Dach et al. 2009; Montenbruck et al. 2014a; Wang et al. 2020; Wang et al. 2016].

This paper focuses on the investigation of a novel code bias for GPS. Its structure is arranged in the following manner. First, the characteristics of conventional code bias products are examined, which serve as a reference for the proposed correction method and precision analysis. Subsequently, the paper explores perspectives on this novel code bias. Finally, the conclusions are presented.

Routine code bias products

Routine code bias products can be classified into two main types. The first type comprises post-processing code bias datasets generated by the Ionosphere and Multi-GNSS Experiment (MGEX) working groups of the International GNSS Service (IGS), with contributions from institutions such as the Chinese Academy of Sciences (CAS), CODE (Center for Orbit Determination in Europe), and Deutsches Zentrum für Luft-und Raumfahrt (DLR). The second category includes real-time broadcast ephemeris parameters, namely Time Group Delay (TGD), Broadcast Group Delay (BGD), and Inter-Signal Correction (ISC), which are disseminated through the satellite broadcasts. This section examines both product types in terms of their correction methodologies and precision evaluation.

Routine code bias product

The International GNSS Service (IGS) set up the MGEX network to advance research in the field of GNSS. It primarily employs receiver models from Septentrio, Trimble, Javad, and Leica (Dow et al. 2009; Montenbruck et al. 2014b). Su and Jiao (2023b) pinpointed four major types of receivers that support multi-constellation observation channels. Using code Observable-specific Signal Biases (OSB) measurements from the Chinese Academy of Sciences (CAS) for the first frequency band of GPS as an instance, Figure 1 presents the time series of the CAS code bias for the GPS C1W code OSB on Day of Year (DOY) 1-120 in 2023. The analysis reveals significant variability in code bias magnitudes across different systems. Specifically, the variations of GPS C1W code OSB ranges within ±15 ns. It is worth noting that the code biases derived from CAS show remarkable temporal consistency over the entire observation period, with no statistically significant variations detected. This consistency underscores the reliability of CAS products for multi-GNSS applications that demand consistent bias characterization.

Broadcast ephemeris parameters

The TGD, BGD, and ISC parameters are broadcast in the navigation ephemeris and are adequate for the real-time PNT service [Wang et al. 2019]. Examples of typical GPS broadcast code biases on DOY 1-120 in 2023 are plotted in Figure 2. The maximum amplitude of the broadcasted code bias variation over four months is 0.5 ns. However, the TGD parameters of some GPS satellites are incomplete.

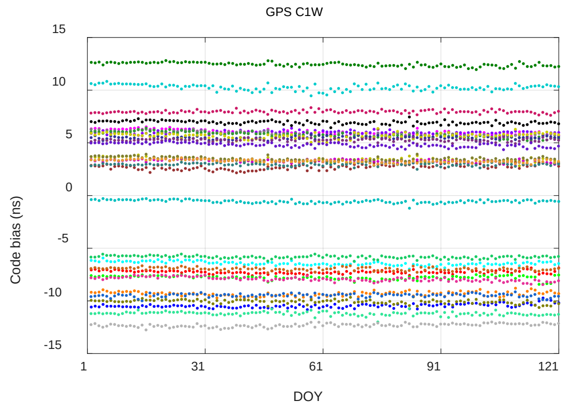

Fig.1 Time series of the CAS code bias for the GPS C1W code OSB on DOY 1-120 in 2023.

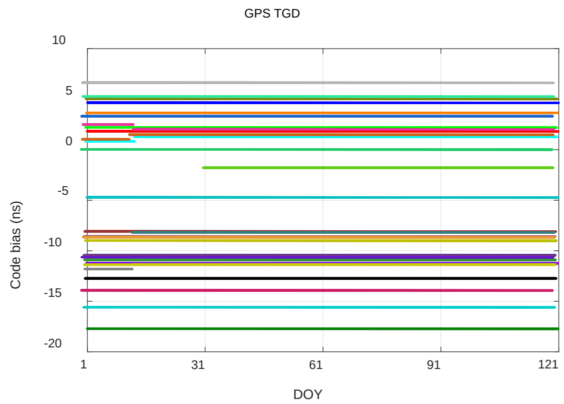

Fig. 2 Time series of the broadcast ephemeris code biases for the GPS TGD on DOY 1-120 in 2023.

Code bias performance

This section outlines the conceptual framework of the new code bias, introduces the mechanism designed for its generation, and analyzes the distinctive features of the code bias product. Additionally, it highlights how the inherent vulnerabilities of space-based PNT systems have spurred the advancement in PNT services [Ming et al. 2023; Ming and Zeng 2022]. Low-frequency incidents, characterized by adaptive power management strategies, encompass spacecraft control system malfunctions, irregularities in time references, ionospheric scintillation effects, and spatial perturbations. These events frequently trigger anomalies or service interruptions in traditional code bias products. Given its pivotal role as a key error contributor and fundamental service element within PNT systems, code bias necessitates uninterrupted availability and high accuracy. The prevalent operational risks underscore the need for preemptive modifications to counteract potential internal and external disturbances in code bias frameworks.

The improved code bias represents an advanced approach that addresses the limitations of conventional products. The latter's limited temporal resolution, as exemplified by hourly updates in broadcast ephemeris, fails to meet the stringent precision requirements under scenarios involving adaptive power management or service degradation. This innovation bridges traditional gaps by enabling defect prevention and system restoration in complex operational settings. A system operates within predefined limits, deviating from standard conditions without experiencing functional collapse. It demonstrates resilience to endure and recover from adaptive power incidents or other threats while optimizing performance for context sensitive PNT provision. The architecture of the novel code bias incorporates three interdependent mechanisms.

Figure 3 presents the operational workflow of the system, which continuously monitors code bias states before, during and after interference events. When external disturbances are detected, the framework initiates a threshold-triggered service mode transition to ensure compliance with PNT requirements, and then reverts to normal operation once the event has passed. The code bias capability metric combines accuracy, efficiency, integrity, and continuity indicators, with performance assessment tailored to specific user needs. While traditional products perform well in stable conditions, the improved framework emphasizes temporal adaptability. This approach allows slight compromises in accuracy during adaptive power scenarios to preserve service continuity and fully restores integrity after disturbances subside.

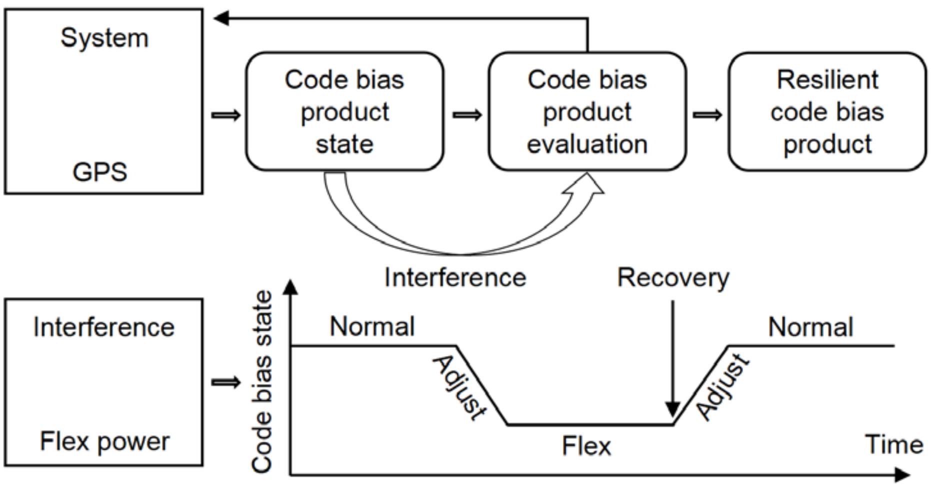

Fig. 3 Flow chart of the novel code bias procedure

Analysis centers such as the CAS, GFZ, and the CODE regularly publish code bias products characterized by low temporal resolution. Current systems are designed to function optimally under stable conditions but lack adaptive features. Therefore, code bias solutions need to ensure compatibility with the characteristics of conventional products during standard operational periods. The mathematical model that enables high temporal resolution estimation of code biases serves as the cornerstone of the proposed solution. Once this high-resolution estimate of code biases is in place, both normal and flex state code biases can be produced in a sequential manner.

The daily estimation of code bias follows a two-step procedure, including linear combination-based bias retrieval and subsequent bias parameterization. Code bias measurements are derived through a linear combination of intra- and inter-frequency geometry-free (GF) function models. For signals sharing identical frequency bands, intra-frequency GF observations eliminate ionospheric delays. The modified carrier-to-code leveling (MCCL) methodology is employed in inter-frequency GF modeling to mitigate impacts of receiver bias temporal variability. Within the MCCL framework, parameters are estimated with distinct process noise levels, in which slant ionospheric delay is 1×10^{5} m^2/s, receiver code bias is 1×10^{-9} m^2/s, inter-frequency bias is 1×10^{-9} m^2/s, and ambiguity terms is 1×10^{-9} m^2/s. These parameters are modeled as white noise or random walk processes, enabling per-channel GNSS code bias resolution.

The ionospheric delay is parameterized using spherical harmonic functions with modified single-layer mapping (MSLM) [Dach & Walser, 2015; Liu et al., 2020]. Corresponding coefficients, along with receiver and satellite biases, follow random walk dynamics with processing noise set to 1×10^{-2}, 1×10^{-11}, and 1×10^{-11} m^2/s respectively. Zero-mean, ionosphere-free, and GF constraints ensure code offset solvability across frequency bands, with differential code bias (DCB) parameters derived accordingly.

To quantify availability, continuity, integrity, robustness, and accuracy, the code bias resilience index (RI) is defined. Four classes are set in the code bias RI, including classes of normality, flexibility, warning and exception, respectively. The novel code bias operates in two distinct modes, that are normal and flex modes, each is characterized by different temporal resolutions. Normal code bias is activated when the RI maintains normalcy over a 24-hour period. In this mode, the RI is calculated as the arithmetic mean of high-resolution RI values, while the code bias itself is derived from the mean of high-temporal-resolution estimates within a sliding window of continuous observation arcs. Flex code bias RI and value are generated in real-time by the engine for each epoch classified under flexibility or warning states. Warning states indicate temporary unavailability to downstream users, while exception states signal engine malfunctions requiring immediate troubleshooting. This dual-mode architecture ensures adaptive performance: maintaining routine precision under stable conditions while dynamically adjusting resolution during anomalies to sustain PNT service continuity.

The GNSS code bias engine, utilizing the Multi-GNSS Positioning and Analysis System (MGPAS) software [Su et al. 2022] , regularly generates code biases, encompassing both the code OSB and DCB, for the GPS. As the cornerstone of code bias products, the high-temporal-resolution code biases are illustrated in Figure 4, covering the period from January to April 2023. Specifically, the figure displays the code OSBs for GPS C1W. These code biases exhibit continuity, with mean standard deviation (STD) values of 0.28 ns for the GPS C1W code OSBs. Notably, the GPS C1W code bias demonstrates slightly superior stability at high temporal resolution than the other types of code biases.

Moreover, Figure 5 presents the RI code bias values and their stability metrics for a randomly chosen set of GPS satellite observed via the GPS C1W observation channel. The selected code biases exhibit a high degree of stability, with STD values recorded as 0.21 ns for GPS G11 C1W. The corresponding RI values for all these biases fall within the range of 0 to 0.5, placing them in normality Category 1. Under this normal condition, the high-temporal-resolution code biases are automatically downsampled to a 1-day temporal resolution.

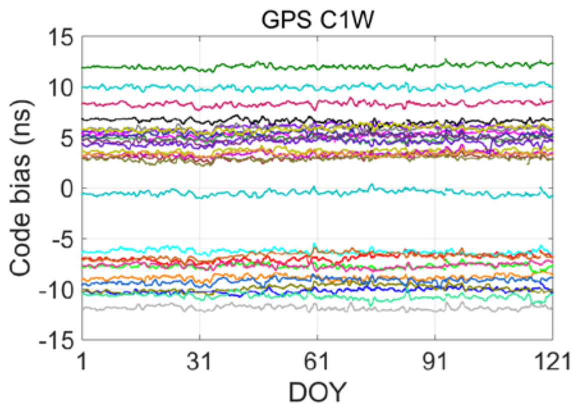

Fig. 4 Time series of the code bias with high temporal resolution in GPS code bias engine from January to April in 2023.

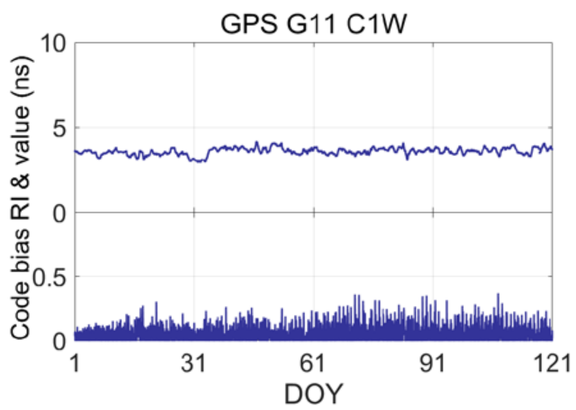

Fig. 5 Time series of the code bias RI and value for GPS satellite.

Concerning GPS code bias, research has revealed that discontinuities of up to 0.8 nanoseconds, with an average magnitude of 0.4 nanoseconds, are attributable to flex power operations [Esenbuğa and Hauschild 2020; Esenbuğa et al. 2023; Steigenberger et al. 2019]. Flex power has a negligible impact on GPS inter-frequency DCB, while it exerts a considerable influence on GPS intra-frequency DCB across the L1 and L2 bands. The specific types of GPS DCB influenced by flex power encompass C1C-C1W, C2W-C2L, C2W-C2S, and C2W-C2X [Esenbuğa et al. 2023]. In October 2023, the GPS control segment conducted two flex power operations targeting Block IIR-M and IIF satellites on the 4th and 24th of the month, respectively. These actions led to a roughly 10 dB boost in signal power on both the L1 (S1W) and L2 (S2W) frequencies for the satellites involved.

Figure 6 displays the S2W carrier-to-noise density ratio (C/N_0) time series data from all GPS Block IIR-M and IIF satellites throughout October 2023, as captured by IGS station CUT0 in Australia. The receiver reliably identified the two-stage power modifications, with C/N_0 variations of approximately 10 dB aligning with the flex power occurrences. Hence, GPS flex power operations can be manifested through C/N_0 observations.

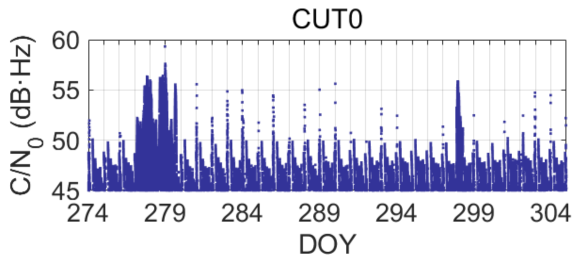

Fig. 6 Time series of the S2W C/N_0 observations of all GPS Block IIR-M and IIF satellites in October of 2023 for the IGS station CUT0.

Figure 7 provides a detailed visualization of the high-temporal-resolution time series data for the C2W-C2L intra-frequency DCB pertaining to GPS Block IIR-M and IIF satellites during October 2023. Although the figure specifically illustrates the C2W-C2L DCB, it is important to note that the other sets of DCBs, namely C1C-C1W, C2W-C2S, and C2W-C2X, demonstrate analogous patterns of variation. Upon examining the data, it becomes evident that all the satellites selected for this analysis exhibit consistent and comparable shifts in their C2W-C2L DCB values throughout the month. Notably, the maximum variation observed in these DCB values is around 0.4 ns, indicating relatively stable yet dynamic behavior influenced by satellite operational conditions.

Figure 8 showcases the resilient C2W-C2L DCB values alongside their corresponding RI values for the randomly selected satellites, namely G06. During periods without flex power adjustments, the DCB time series demonstrate a stable pattern, with RI values remaining consistently below 0.5. Conversely, during flex power operations, the RI experiences a marked surge to approximately 0.5, signaling the transition of the DCB into a flex state. It is particularly noteworthy that the magnitude of DCB fluctuations during the initial flex power event was substantially greater than that recorded during the subsequent event. The GPS flex power operations can be clearly visualized.

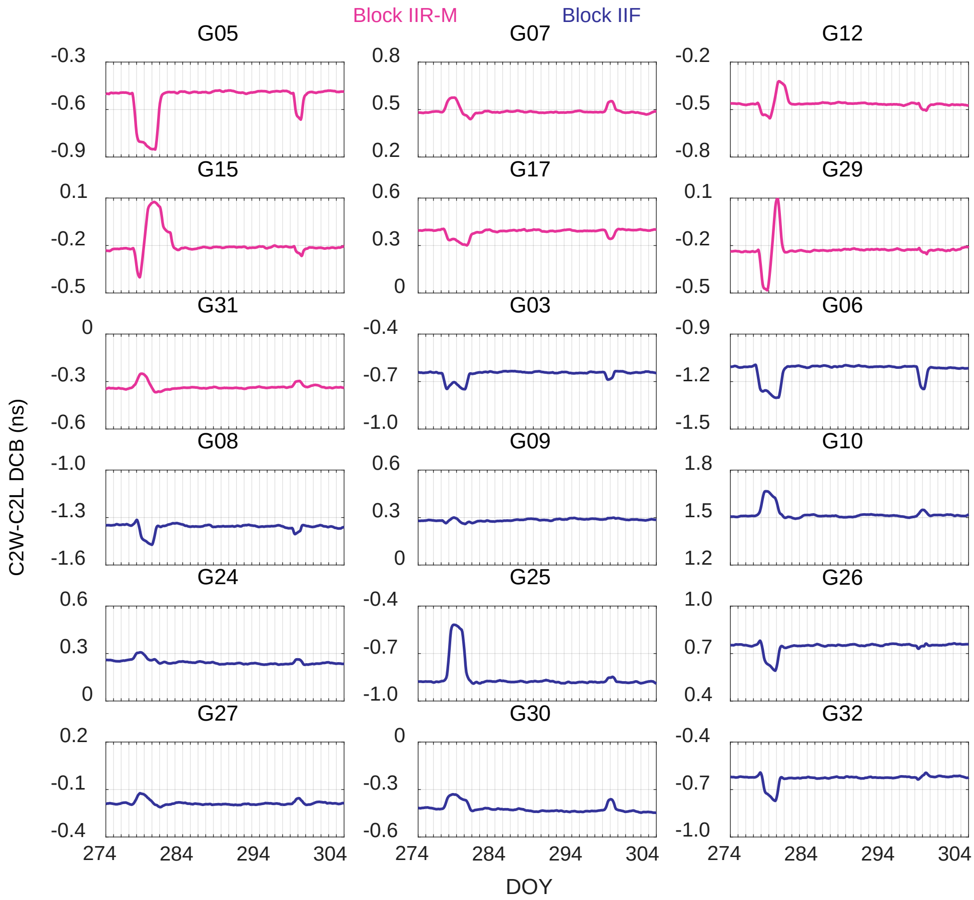

Fig. 7 Time series of the GPS C2W-C2L intra-frequency DCB value with high temporal resolution for the GPS Block IIR-M and IIF satellites in October of 2023.

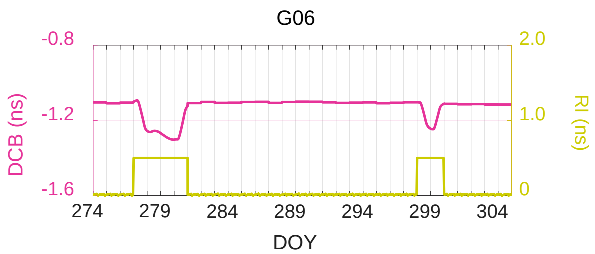

Fig. 8 Time series of the resilient GPS C2W-C2L intra-frequency DCB value and RI of randomly selected G06 satellites in October of 2023.

Figure 9 displays the time series data of resilient GPS C2W-C2L intra-frequency DCB values for Block IIR-M and IIF satellites throughout October 2023, accompanied by the corresponding CAS daily code bias values for comparative analysis. The GPS variations are characterized by small magnitudes, staying within the subnanosecond range. The root mean square (RMS) differences between the DCBs and the CAS reference values are 0.03 ns and 0.09 ns, respectively. This indicates that both the DCB estimates, despite their differing temporal resolutions, provide reasonable approximations of GPS code bias and meet the requirements for GNSS PNT services.

We specifically chose days when GPS implemented flex power operations to carry out a kinematic Precise Point Positioning Ambiguity Resolution (PPPAR) experiment. During this experiment, we evaluated the enhanced PPPAR performance and compared it with results obtained using products from a conventional approach that did not incorporate the impact of flex power. In the figures, different processing strategies are distinguished by distinct colors. Figure 10 illustrates the time series of GPS PPPAR positioning errors during periods of GPS flex power operations. The positioning errors after convergence are also presented in the figure, with the convergence threshold set at 0.1 m. It is evident that the optimized algorithm can, to varying extents, improve the performance of GPS PPPAR performance.

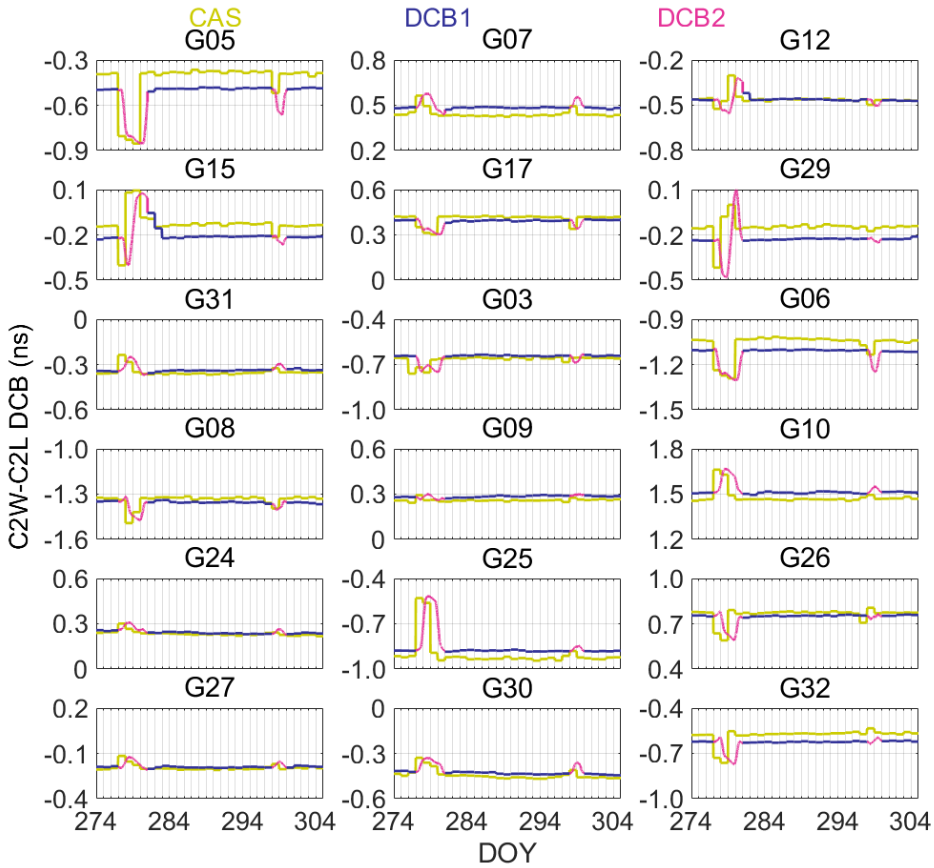

Fig. 9 Time series of the resilient GPS C2W-C2L intra-frequency DCB value for the GPS Block IIR-M and IIF satellites in October of 2023.

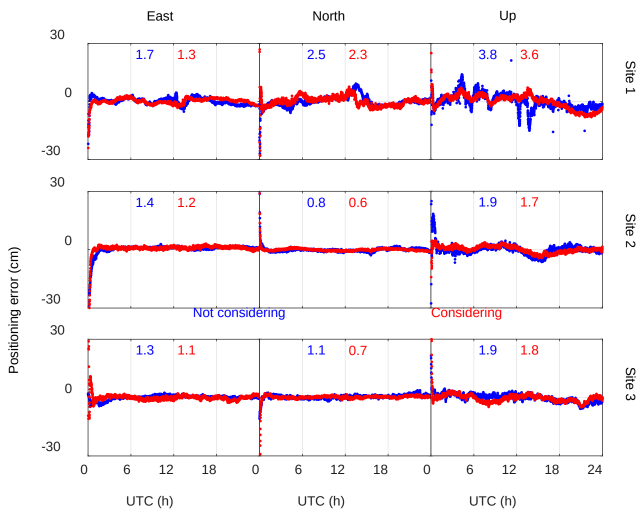

Fig. 10 GPS PPPAR on DOY 277 in 2023 affected by GPS flex power

Conclusion

This paper presents a comprehensive analysis of a novel code bias solution designed specifically for GPS operating under flex power conditions, addressing the limitations of conventional code bias products that fail to accurately capture rapid variations induced by flex power operation. By introducing a code bias framework with dual operational modes, the proposed solution ensures adaptive performance, by maintaining routine precision during stable conditions while dynamically adjusting resolution during anomalies to ensure PNT service continuity.

Through rigorous analysis and experimental validation, the study demonstrates that the novel code bias solution not only maintains compatibility with conventional products during standard operations but also demonstrates superior environmental adaptability and enhanced performance under complex conditions induced by flex power management. The high-temporal-resolution code bias estimates, derived through a robust mathematical model, enable precise characterization of code bias behavior. Furthermore, the code bias capability metric, which integrates accuracy, efficiency, integrity, and continuity indicators, provides a comprehensive assessment framework customized to specific user requirements. Experimental results from kinematic PPPAR experiments conducted during GPS flex power intervals validate the effectiveness of the optimized algorithm in improving GPS PPPAR performance, with positioning errors being significantly reduced compared to conventional approaches.

In conclusion, the proposed novel code bias solution represents a significant advancement in the field of GNSS PNT services, providing a robust and adaptive framework that is capable of meeting the diverse and evolving requirements of modern applications. Future research will focus on further optimizing the code bias estimation methodology, assessing its applicability across a wider range operational scenarios, and facilitating its integration into PNT service infrastructures to enhance their overall reliability.

Acknowledgment

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Data Availability

The GNSS observation data used is provided by the MGEX network (ftp://igs.ign.fr/pub/igs/data/campaign/mgex/daily/rinex3/). The CAS code bias products are provided by CAS (ftp://ftp.gipp.org.cn/product/dcb/mgex/).

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